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DEVELOPMENT OF PVF_2 NOISE-CANCELLING MICROPHONE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the theory, development, and performance of a noise-cancelling microphone for military use. The generating element is a bimorph annulus, constructed by bonding plastic films of piezoelectric PVF_2 (polyvinilidene fluoride) to a central shim of aluminum. The aluminum shim controls the stiffness of the bimorph so that wide-bandwidth operation is obtained over a temperature range of -51°C to +71°C. The fundamental → next page

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20. ABSTRACT (Continued)

resonance frequency is above the speech frequency range so that damping structures are not required. The microphone includes a preamplifier.

The microphone assembly is similar to that of a previously developed piezoceramic microphone. The sensitivity of the PVF_2 bimorph is 10 dB less than that of the piezoceramic bimorph. The PVF_2 film has a deposited aluminum electrode which was found to require careful handling to avoid loss of electrical continuity.

Except for considerations of the integrity of the PVF_2 electrode, the PVF_2 material provides a rugged, highly-linear, noise-cancelling microphone.

CONTENTS

1.0 INTRODUCTION

The purpose of this project is to develop a noise-cancelling microphone which uses a synthetic polymer, polyvinylidene fluoride (PVF_2), as the voltage-generating element. The suitability of this type microphone for military use is to be determined. Figure 1 is an outline drawing of the microphone. The Vought Advanced Technology Center designation is Model NCMA-103. Ten microphones were delivered to the U. S. Army for further evaluation.

Polyvinylidene fluoride is a physically tough, relatively inert, fluorocarbon plastic. In the United States it is produced under the trade name KYNAR by Pennwalt Corporation, Philadelphia, PA. An important producer in Japan is Kureha Chemical Industry Co., Ltd.

It has been known for many years that some naturally-occurring and synthetic organic materials are piezoelectric, or can be rendered piezoelectric by treatment. In 1969, in Japan, H. Kawai[1] discovered that polyvinylidene fluoride is capable of a high level of piezoelectricity. Since that time, this property has been exploited in various types of experimental and commercial electroacoustic transducers. At the present time, the use of PVF_2 for military transducers is still in the exploratory stage.

The piezoelectric material used for the PVF_2 microphone was a purchased plastic film, having deposited aluminum electrodes on both sides of the film, and already processed to make it piezoelectric. Typical processing steps are as follows:[2,3]

- Raise the film temperature to approximately 90°C and rapidly stretch the film uniaxially to 3 or 4 times its original length.
- Deposit aluminum electrodes (or some other metal).
- Raise the film temperature to approximately 130°C and apply an electric field of 800 kV/cm between the electrodes for 1 hour.
- Cool the film before removing the electric field.

Stretching the film before poling enhances the piezoelectric effect by changing the crystal structure and by orienting the crystals. After the film is poled, a voltage is induced between the electrodes when the film is strained in the "stretched" direction. The voltage is proportional to the strain. If the same

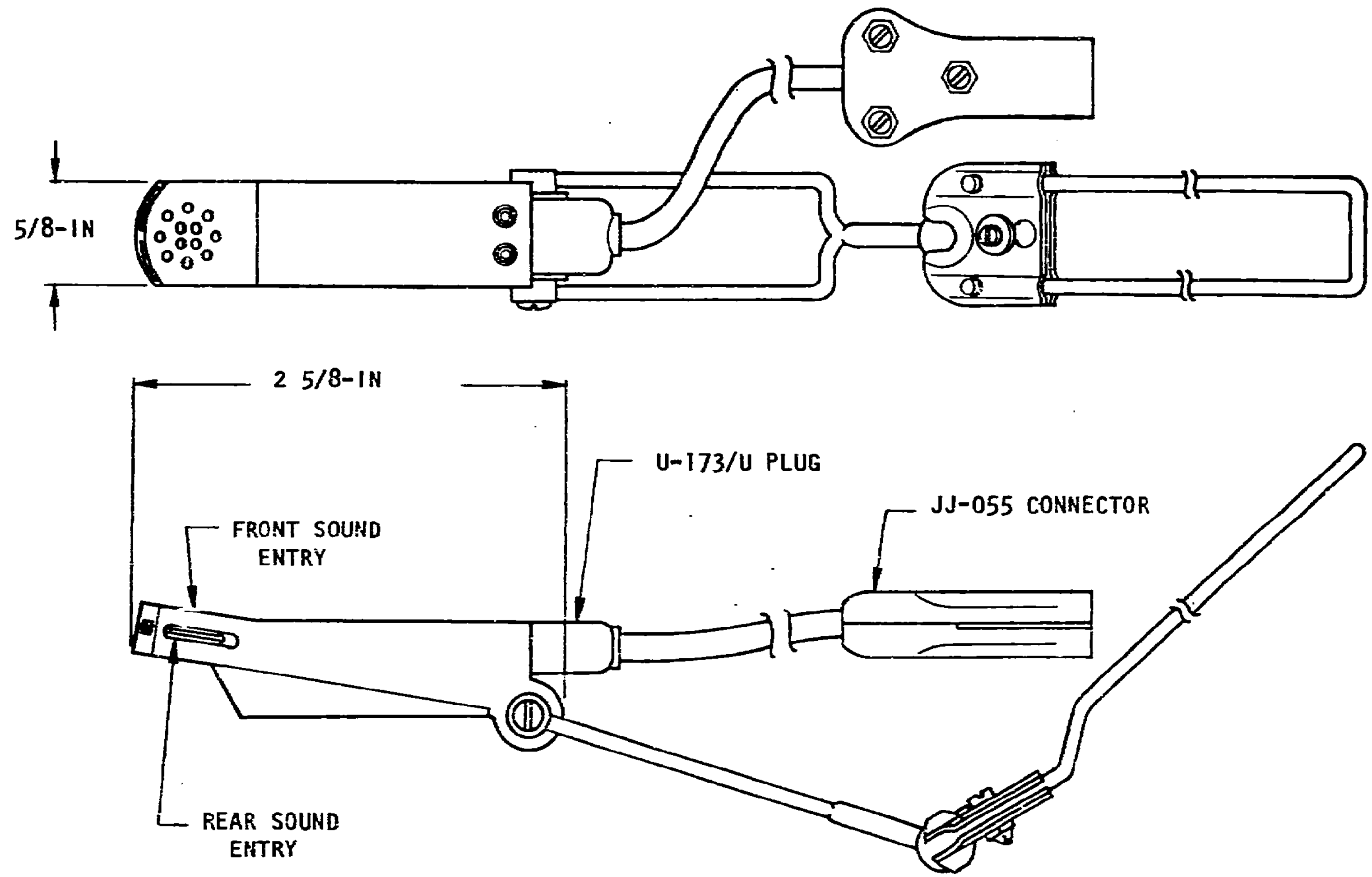


FIGURE 1. PVF_2 MICROPHONE, MODEL NCMA-103

stress is applied in the plane of the film, but normal to the stretched direction, a voltage is induced which has the same sign as before, but which is only about 10% as large.

The poled PVF_2 is also an electret; however, the deposited electrodes allow induced charges on the electrodes to neutralize the external electric field usually associated with an electret. The poled PVF_2 film is also pyroelectric. PVF_2 film has been used as a detector of heat radiation.

Table 1 shows a comparison between the properties of poled PVF_2 and a commonly-used piezoceramic material. Under an earlier contract, a piezoceramic, noise-cancelling microphone, Advanced Technology Center Model NCMA-102, was successfully developed for the U. S. Army.[4] The PVF_2 microphone and the earlier piezoceramic microphone have a number of common constructional details.

A project to make a PVF_2 microphone for military applications presents several challenges:

- The PVF_2 material is relatively compliant. A configuration must be devised which has sufficient stiffness so that the specified response bandwidth of 200-6000 Hz is achieved.
- The aluminum electrodes must be protected from corrosion. Water must be prevented from reaching and shorting the electrodes during rain or water-immersion.
- The modulus of elasticity of most polymers is highly temperature dependent. The compliance of the PVF_2 element must be stabilized so that the microphone sensitivity does not change prohibitively over the specified operating temperature range of -51°C to +71°C.
- During preparation, the PVF_2 film has been severely stretched at a relatively low temperature. It may be dimensionally unstable at elevated temperatures, unless constrained.
- Due to the relatively low capacitance (high impedance) of the PVF_2 element, a high impedance, well-shielded, preamplifier must be provided.

TABLE 1. COMPARISON BETWEEN PVF_2 AND G-1195 (LEAD ZIRCONATE TITANATE)

	PVF_2*	G-1195**
Density kg/m^3	1780	7500
Young's modulus N/m^2	3.0×10^9	80×10^9
Dielectric constant ϵ/ϵ_o	13	2000
g_{31} volt - m/N	174×10^{-3}	11×10^{-3}
d_{31} m/volt	20×10^{-12}	180×10^{-12}
Coupling coefficient %	10	30

* Data from Kreha Corp. of America, a subsidiary of Kureha Chemical Industry Co., Ltd.

**Data from Gulton Industries, Inc.

2.0 PERFORMANCE OF THE PVF_2 MICROPHONE

2.1 POWER SUPPLY CONNECTION

Figure 2 shows the power supply connection for testing the microphone. The electrical load on the microphone is 150 Ω. If the resistance of the ammeter is appreciable, it may be shorted. The microphone connector is non-polar.

2.2 ACOUSTICAL PERFORMANCE

Table 2 shows the typical performance of the PVF_2 microphones which were delivered to the U. S. Army. The sensitivity and output impedance of individual microphones is adjusted by selection of resistors in the preamplifier.

The sound-source for the close-talk measurements (1/4-inch distance to source) was constructed according to U. S. Air Force Drawing 58B12627 (approved 30 June 1958). In this source, the sound port is essentially a 1/4-inch diameter hole, located in the side wall of a long, 1 5/8-inch diameter tube. A speaker is coupled to one end of the tube. The other end has a sound absorbing termination. In Appendix C, there is a discussion of the effect of the sound-source in determining the measured sensitivity and noise-immunity.

Noise immunity is defined as the difference between the on-axis, close-talk sensitivity and the on-axis, distant-source sensitivity. The distant-source measurement was made at a distance of 1-meter from a 12-inch diameter loudspeaker in an anechoic chamber.

Figure 3 shows the microphone response and noise-immunity. Figure 4 illustrates the polar response of a representative microphone. The polar response at 2000 Hz (and all frequencies below 2000 Hz) is effectively a perfect cosine pattern. When tested with the same sound-source, the previous Model NCMA-102 microphone has about 2 dB better noise-immunity at 1000 Hz than the PVF_2 microphone. However, the PVF_2 microphone is better above 3000 Hz. The PVF_2 microphone has about 3 dB better noise-immunity at 1000 Hz than the well-known M-87 dynamic microphone. The polar response of the PVF_2 microphone is also better than that of the typical M-87.

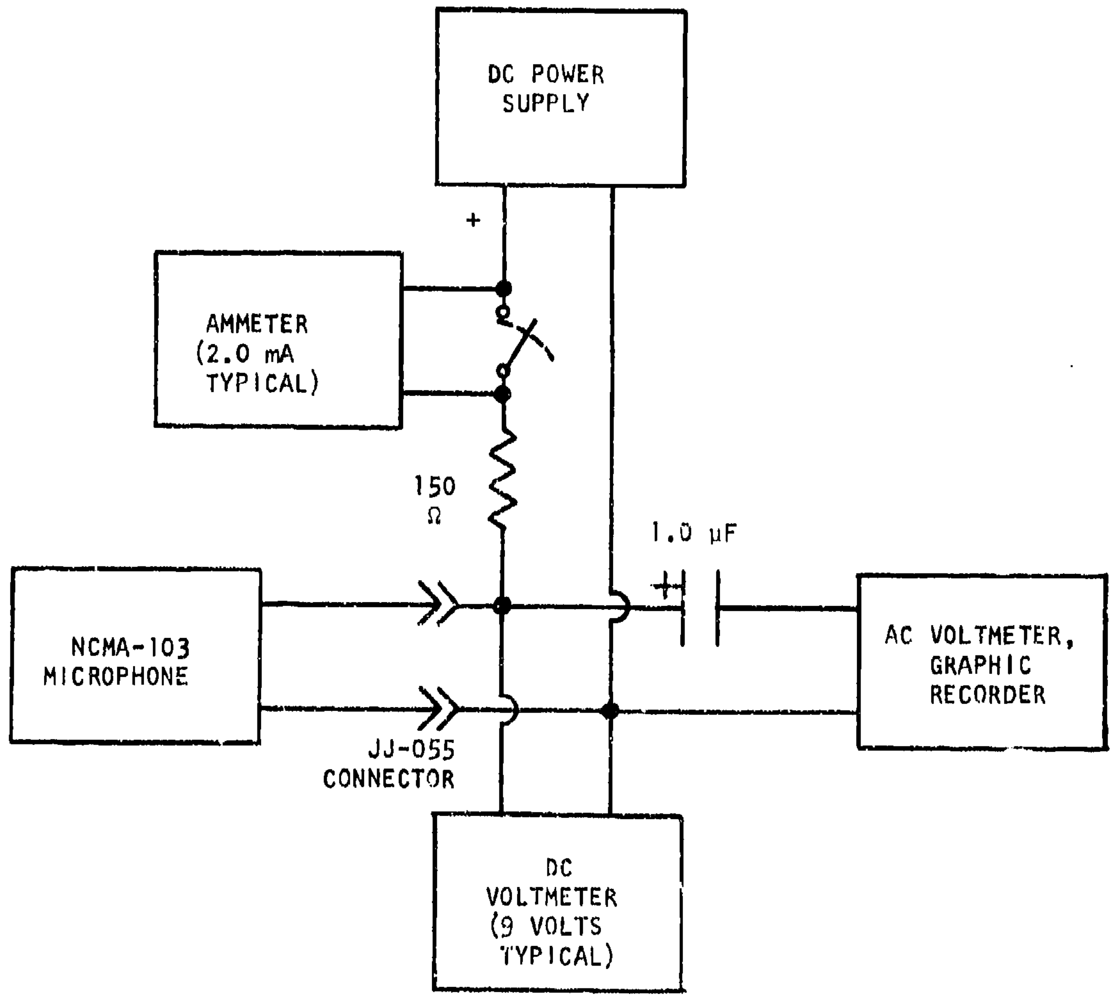


FIGURE 2. POWER SUPPLY CONNECTION

TABLE 2

TYPICAL PERFORMANCE
NOISE-CANCELLING MICROPHONE MODEL NCMA-103
1st-ORDER GRADIENT

Type	PVF_2 piezoelectric, with integral preamplifier
Power Supply	Typical: 9 Vdc at connector; 2.0 mA current
Power Supply Limits	Minimum: 1.0 mA, approx. 7.0 volts at connector Maximum: 6 mA, approx. 16 volts at connector
Sensitivity	-90 dBV/μbar (900 μvolts/28 μbar) across 150 Ω load at 1000 Hz, 1/4-inch to source
Output Impedance	150 Ω resistance at 2.0 mA current
Frequency Response	200-6000 Hz ±2 dB; response extends to 12 kHz
Noise Immunity	12 dB at 1000 Hz, average for 0° and 180° incidence
Harmonic Distortion	<1% at 130 dB SPL <5% at 140 dB SPL
Vibration Sensitivity	Equivalent to 110 dB SPL/G at 400 Hz
Self Noise	Equivalent to 52 dB SPL, A-weighted
Connector	Accepts U-173U plug
Weight	55 grams, including boom and 8-inch cord assembly
Case Material	Lexan (a General Electric polycarbonate)
Case Color	Black

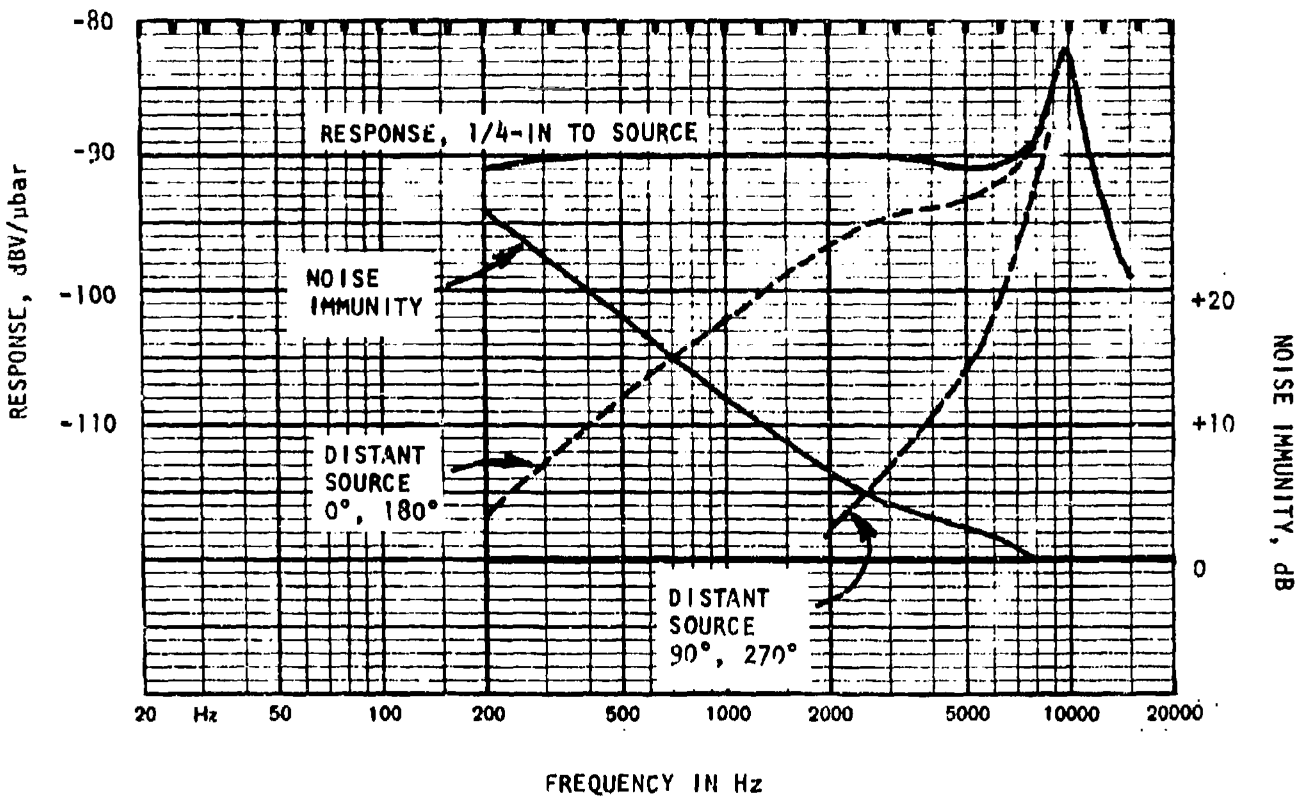


FIGURE 3. RESPONSE OF PVF_2 MICROPHONE

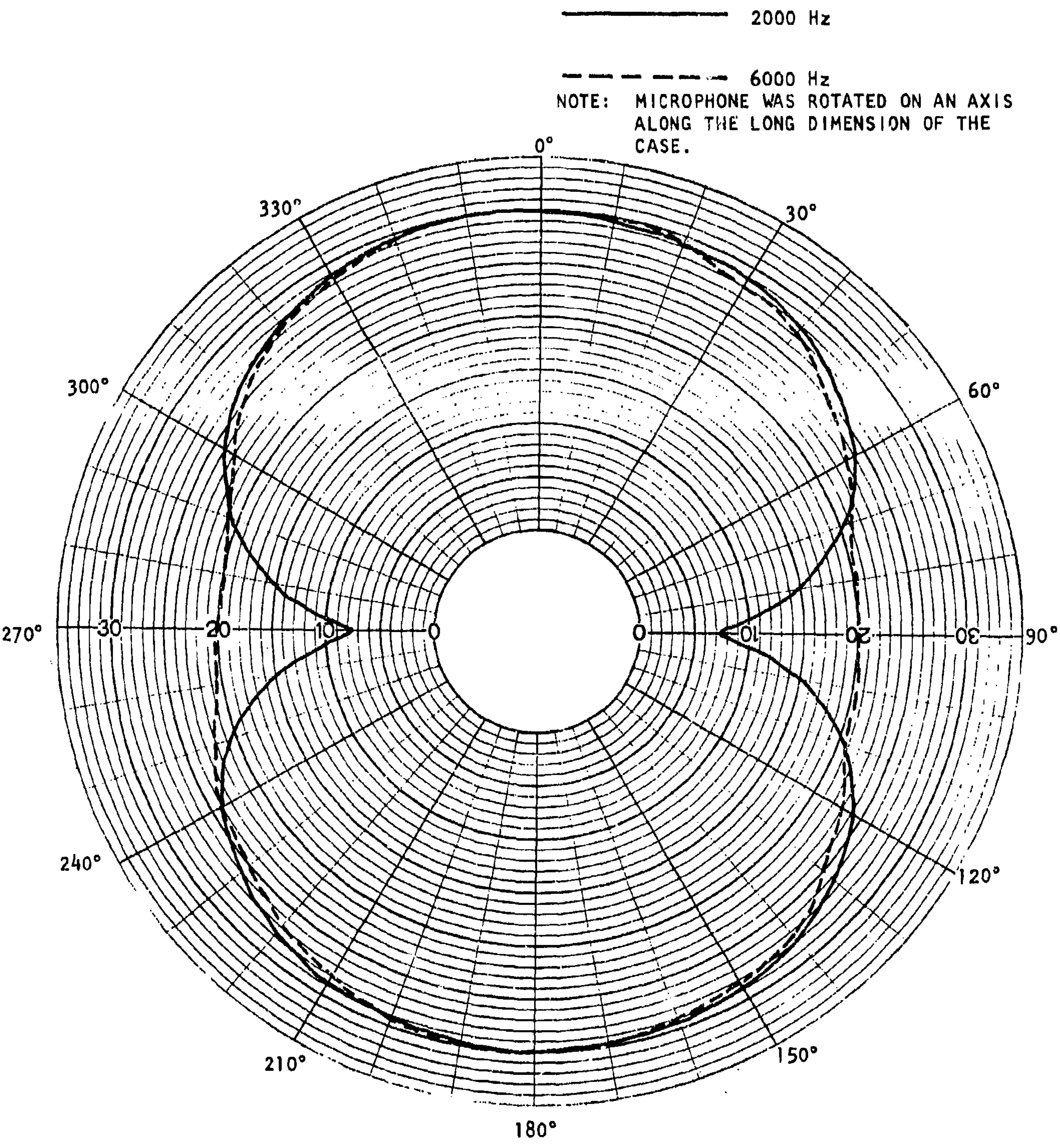


FIGURE 4. POLAR RESPONSE OF PVF_2 MICROPHONE.

3.0 MICROPHONE DEVELOPMENT

3.1 DEVELOPMENT APPROACH

In dynamic and magnetic microphones, the lowest mechanical resonance of the diaphragm assembly is placed near the center of the frequency range of interest, and acoustic damping is employed to smooth the response. The damping is susceptible to change due to aging of the damping material. The damping structure will trap water during water immersion so that water-tight, but pressure-equalized, flexible membranes must be provided to protect the material and permit sound to pass. Finally, the damping structure and flexible membranes compromise the acoustical symmetry of the noise-cancelling system, causing a reduction in noise immunity.

In the piezoceramic microphones previously developed at ATC,[4] the lowest mechanical resonance of the diaphragm assembly was placed near or above 10 kHz, above the speech frequency range of interest. Damping is not required. This is the approach selected for the PVF_2 microphone.

Two diaphragm structures were investigated during the project.

- A spherical dome (shell), wherein sound pressure induces a tangential stress.[5,6] This structure was tested and abandoned.
- An annular bimorph, such as used in previous piezoceramic, noise-cancelling, microphones.[4,7]

3.2 PVF_2 FILM

PVF_2 film was purchased from Kreha Corporation of America, New York 10017. Both 9 µm (0.35-mil) thick and 30 µm (1.2-mil) thick films were available. The film was uniaxially stretched and poled as received and had vapor deposited aluminum electrodes on both sides. Only the 30 µm film was used during the project.

Four samples of PVF_2 film were received from the Pennwalt Corporation Technological Center, King of Prussia, PA 19406. Three of the films were uniaxially oriented (stretched), one was biaxially oriented. Thicknesses ranged from 0.4-mil to 2.8-mil. Pennwalt at that time (1977) was still developing its production and electroding processes. The electrode coating on the Pennwalt film came off more easily than that on the Kreha film. For this reason all experimental microphones were made with the Kreha film.

In a recent communication (December 1978), Pennwalt claims that they have now developed an improved deposited-nickel electrode for their PVF_2 film. Commercial production is expected in 1979. This may be an important development since, as reported below, the fragility of the aluminum electrode was the main problem encountered with the Kreha film. It was also found that, without protection, exposure of the Kreha film to 100% relative humidity at 65°C for several days causes the aluminum electrodes to come off.

Early in the development program it was decided that the PVF_2 film would need to be bonded to a stable substrate for use in military microphones. The substrate, such as aluminum, would control the flexural rigidity of the PVF_2 element. The compliance of the element would then be relatively independent of temperature.

3.3 PVF_2 BIMORPH

Figure 5 shows the bimorph developed for the PVF_2 microphone. A ring of PVF_2 film is epoxied to each side of a central shim of 9.5-mil thick aluminum. A water-barrier of 1-mil Kapton (polyimide) is then epoxied to one of the PVF_2 films. A combination 1-mil dome and water-barrier is epoxied to the other PVF_2 film. The assembly is held together in a press at 55°C until the epoxy cures. Finally epoxy is used to seal the inner periphery of the ring. The epoxy is Emerson & Cuming 45 LV, with 15 LV catalyst. The Kapton dome is formed in a hot mold prior to assembly into the bimorph.

The tabs on the PVF_2 films are used as leads. The PVF_2 films are oriented with like poles facing. If the inward-facing electrodes are shorted, the voltage measured between the outward-facing electrodes is the sum of the voltages produced by each film, if the bimorph is bent such as shown in Figure 5(c).

The silicone-rubber rings provide a simple (hinged) support. The series-connected bimorph shown in Figure 5 has the following performance:

Sensitivity:	-97 dBV/µbar (in the noise-cancelling configuration)
Capacitance:	120 pF (240 pF for each PVF_2 ring)
Resonance Frequency:	10,000 Hz

There is a high peak of response at 10,000 Hz. This is attenuated in the microphone by a low-pass filter in the preamplifier. The PVF_2 bimorph is

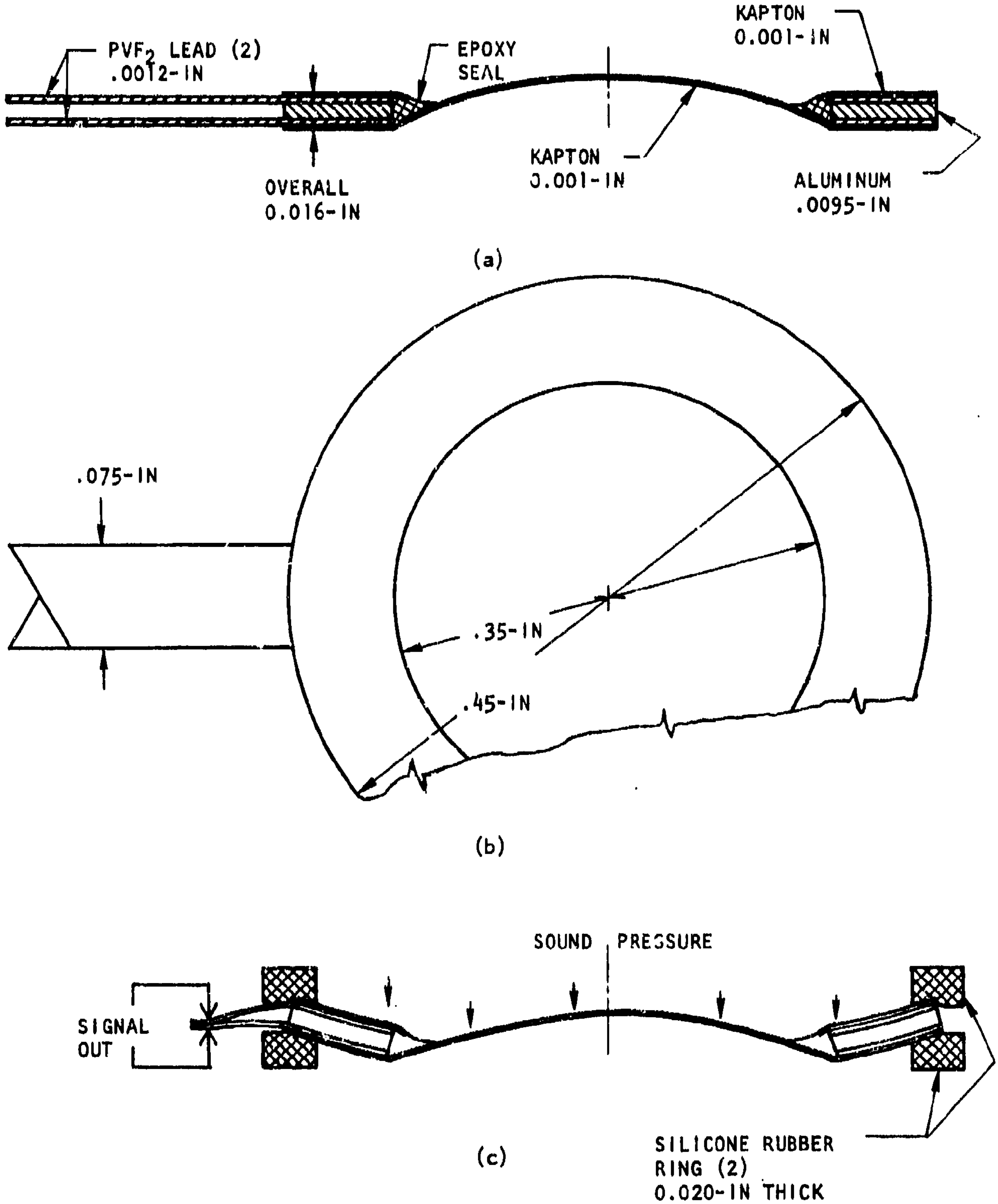


FIGURE 5. PVF_2 BIMORPH

about 10 dB less sensitive than the piezoceramic bimorph used previously.[4] The theoretical performance of the PVF_2 bimorph is discussed in Appendix A. The environmental performance is discussed in Section 4.

Before adopting epoxy as the bonding agent, an attempt was made to use a dry film of thermoplastic cement so as to form the bimorph in a simple hot-press. The central dome was formed in the same operation. A polyester adhesive, Sheldahl GT-100, was used to bond the PVF_2 to the aluminum. A laminate of Mylar and polyester adhesive, Sheldahl GT-300, was used as the water-barrier and dome. Although good-looking bimorphs were made, the sensitivities were at least 10-20 dB less than expected. It was concluded that the heat [typically 141°C (285°) for 5 minutes] was causing depolarization of the PVF_2.

3 4 PVF_2 DOME CONFIGURATION

An experimental dome-microphone was built using the PVF_2 film. The dome-microphone was found to have an irregular response. The dome quickly became deformed upon exposure to elevated temperatures. Further discussion of the theory and construction of the dome-microphone is found in Appendix B.

3.5 CAPSULE ASSEMBLY

The capsule assembly is shown in Figure 6. The chassis is made of three brass pieces, soldered together. The chassis and grille are given a chemical-black treatment as per MIL-F-495C using formulation ENE-BLACK L26 provided by Enequist Chemical Co., Brooklyn, NY. The grille, support rings, bimorph, and chassis are assembled together in a rollover die.

The use of silicone rubber for the support rings is essential to maintain flexibility at -51°C. This was demonstrated by tests made during an earlier project.

The exit point for the leads is through a square brass tube which is part of the chassis. Contact to the leads is made by means of an 0-80 stainless-steel screw. The lead assembly is stacked in the following order:

- S/S screw threaded in brass tube (electrical common)
- Tinned copper pad, to prevent damage to PVF_2 tabs.
- Upper PVF_2 tab
- Lower PVF_2 tab

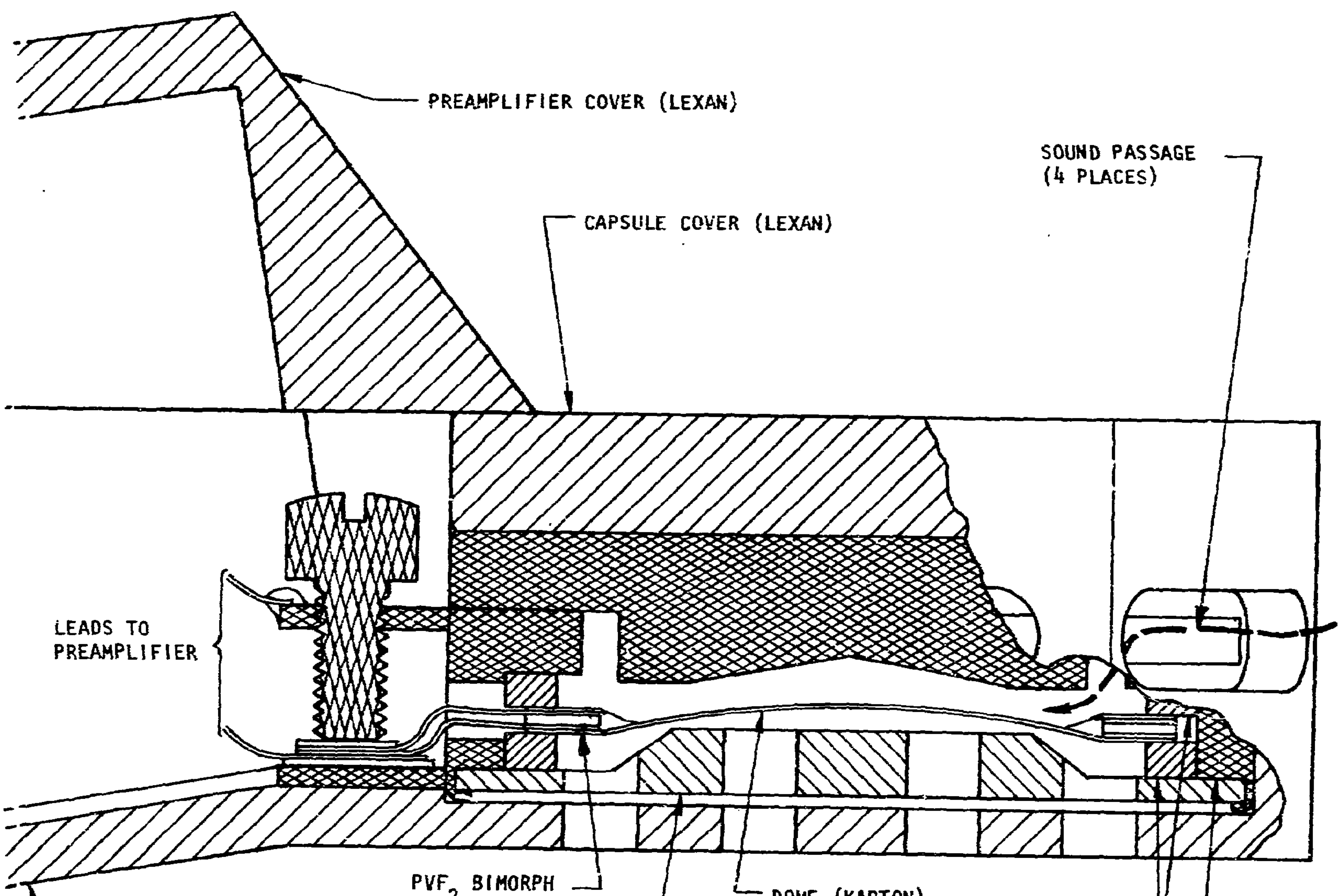


FIGURE 6. MODEL NCMA-103 DETAIL

- Tinned copper lead (signal out)
- Insulating tape
- Bottom wall of brass tube

The front sound entry is at the grille. The rear sound entry consists of four slots in the capsule which match four slots in the microphone case. The rear entries are at the sides of the case, an arrangement which has been found to provide good noise-cancelling performance. After the capsule is epoxied into the case and the leads are attached to the preamplifier, the opening in the square brass tube is blocked. The preamplifier is potted in the case with Dow Corning SYLGARD 184 resin. The preamplifier cover is then epoxied to the case, completing the assembly.

In the final assembly, water is prevented from getting to the bimorph leads by the Kapton water-barriers, by the silicone-rubber support rings, and by the blocked and potted brass tube.

3.6 PREAMPLIFIER

Figure 7 is the preamplifier circuit. The principal requirement is for impedance transformation from the high capacitive reactance of the bimorph to the required output impedance of 150 Ω. The preamplifier has a common source field-effect-transistor stage (FET) stage followed by a common-collector bipolar-transistor stage. When driving a 150 Ω load, the amplification of the preamplifier is 7 dB. This includes a 3.5 dB insertion loss due to the shunting effect of the 60 pF input capacitance of the first transistor stage. The voltage amplification of the first stage is about 22 dB which raises the signal level so that little noise is added in the second stage. The output of the second stage is attenuated by the series and shunt resistors in the output circuit, and additionally at high frequencies by the inductor-capacitor, low-pass filter. The first stage does not employ negative feedback; therefore adjustment of gain by resistor selection is necessary.

The gain and output impedance are functions of power supply current, primarily due to changes in the dynamic resistance of the diodes in the bridge circuit. The bridge resistance ranges from about 48 Ω at 2 mA current to about 17 Ω at 6 mA current. As the supply current is increased, the output impedance goes down somewhat, and the microphone sensitivity goes up slightly.

*SELECT TO ADJUST GAIN AND CURRENT

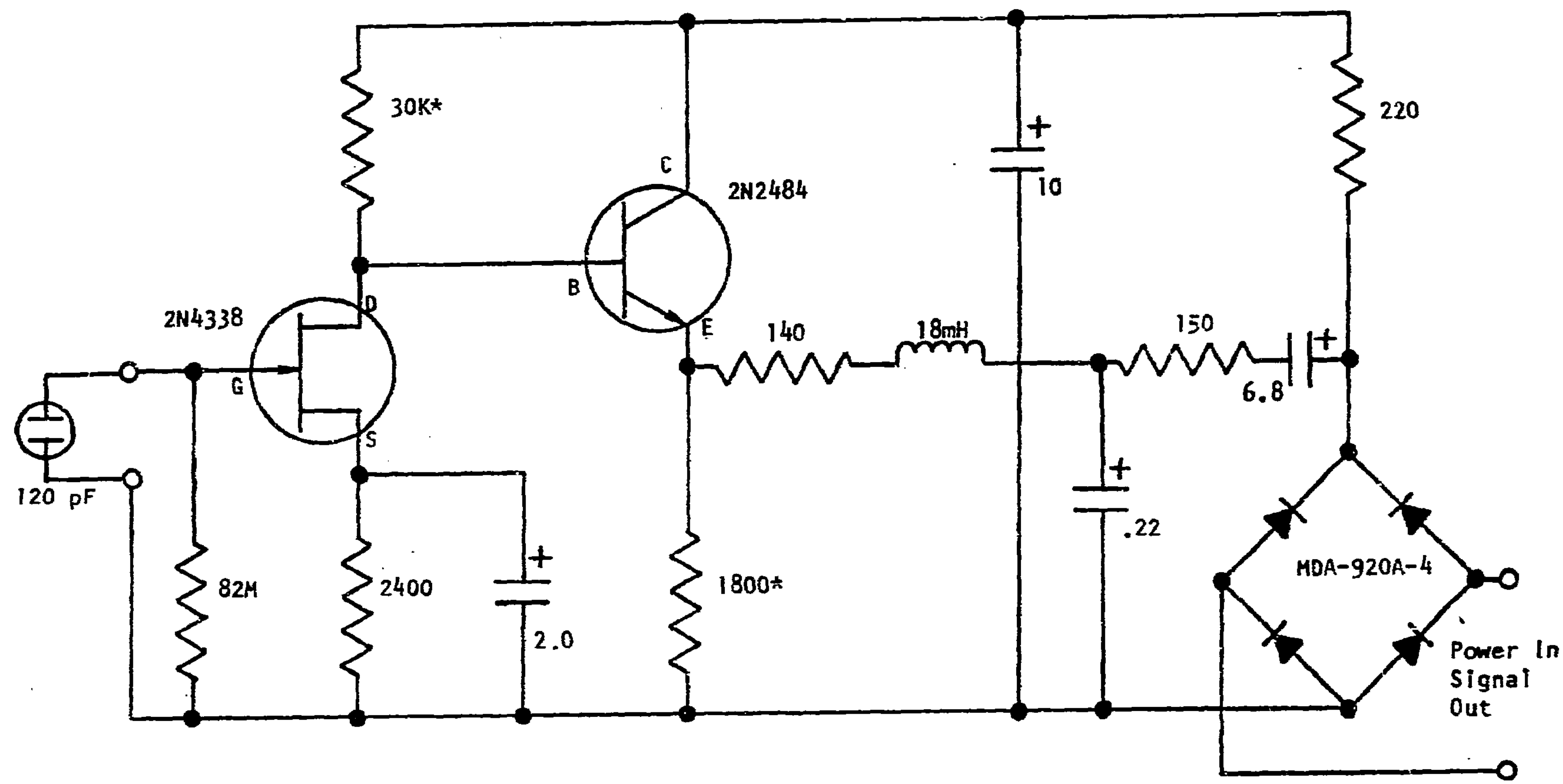


FIGURE 7. MODEL NCMA-103 CIRCUIT

The preamplifier amplification characteristic at a nominal 2.0 mA is shown in Figure 8. A self-noise curve is also shown.

The bimorph is shielded in a housing as shown in Figure 6. This shielding is extended to the preamplifier housing by painting the inside of the case with conductive paint. The shields are tied to the "common" of the preamplifier circuit. Although quantitative measurements were not made, hum pickup appears to be low.

The preamplifier is assembled conventionally on a printed circuit board.

A ferrite shield bead, Fair-Rite Products Type 1, Part No. 2643000101 is strung on each of the preamplifier output leads, inside the case, to block entry of RF energy. EMI testing was not performed on the microphone.

3.7 BATTERY POWER SUPPLY

A small battery power supply is supplied with each of the production microphones. Designed to be mounted on a crewman's helmet on the same post as the boom, the supply makes operation of the microphone independent of vehicle power. The supply circuit is shown in Figure 9. The battery supply is designed to not load the microphone. With a 15 Vdc battery, the dc voltage at the microphone is about 10.5 volts. The microphone should be unplugged when not in use to save the battery.

Due to the extended low-frequency response of the microphone, rather large low-frequency transients are produced by bumping the case or from the user's breath while speaking. Although these transients do not overdrive the preamplifier, they were observed to overdrive a wide-band power amplifier during testing. This was solved by placing a suitable high-pass filter at the input of the power amplifier.

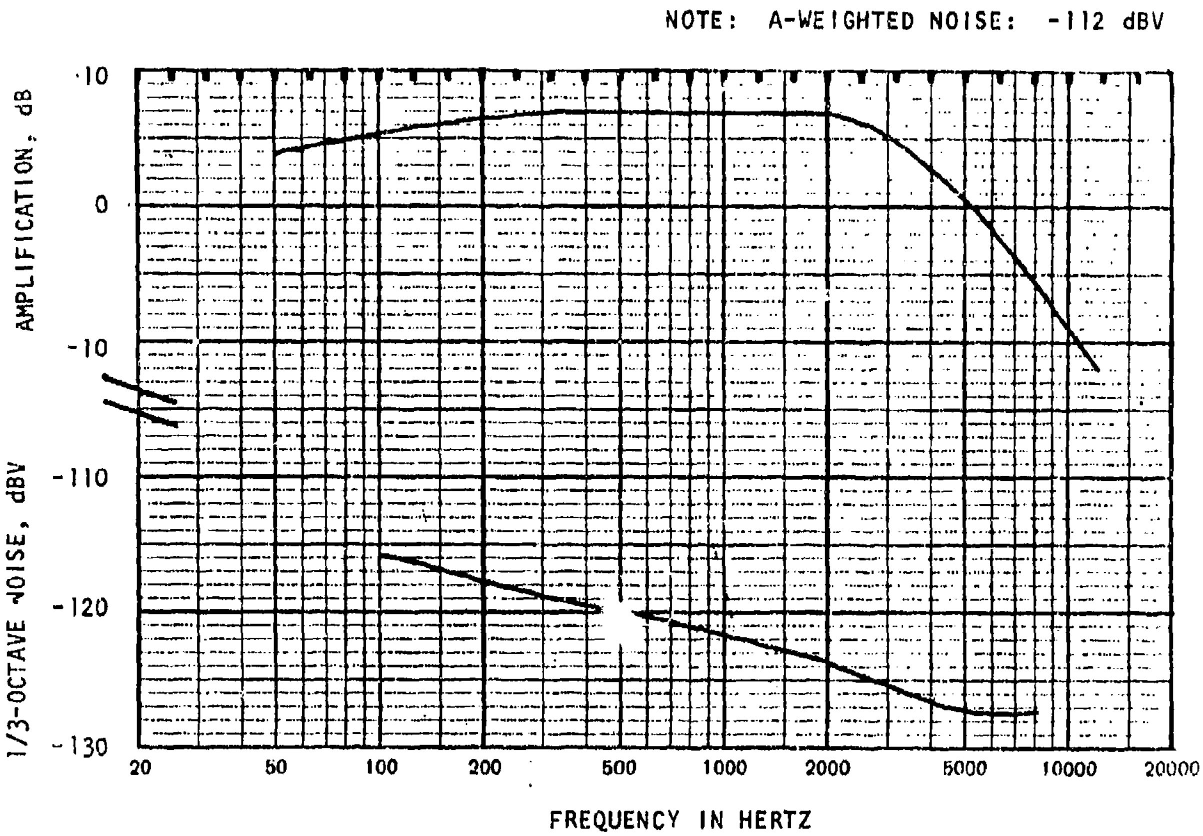
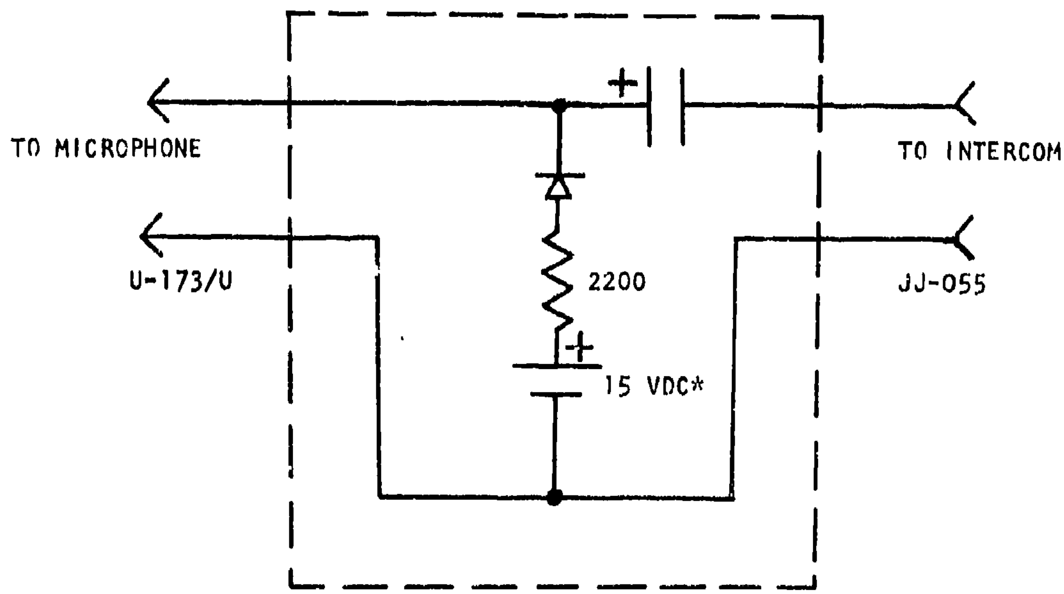


FIGURE 8. PRE-AMPLIFIER RESPONSE AND NOISE



*EVEREADY #411 OR EQUIVALENT,
BATTERY LIFE > 30 HOURS AT
2 mA DRAIN

FIGURE 9. BATTERY POWER SUPPLY

4.0 ENVIRONMENTAL PERFORMANCE

4.1 ACCELERATION RESPONSE

Figure 10 shows the acceleration response of the PVF_2 microphone, compared to that of a previously developed piezoceramic microphone. The response was measured along on axis approximately perpendicular to the plane of the bimorph. The attachment to the shaker was made on the flat area of the case between the microphone grille and the connector.

The peak near 2000 Hz is due to a mechanical resonance of the microphone case. The frequency of the peak depends on the placement of the microphone on the shaker. The acceleration sensitivity of the PVF_2 microphone is 3 to 7 dB greater than that of typical dynamic and magnetic microphones. The Model NCMA-102 employs a special bimorph configuration designed to reduce the vibration sensitivity.[4] Use of the special bimorph configuration in the PVF_2 microphone would greatly reduce its vibration sensitivity. There would be a penalty of about 3 dB loss of sensitivity which would be compensated by increasing the gain of the preamplifier. The net effect would be a 3 dB increase in the self-noise of the microphone.

4.2 HIGH AND LOW TEMPERATURE OPERATION

Figure 11(a) is a plot of microphone sensitivity versus ambient temperature (solid curve). Also shown in Figure 11(a) is the effect of ambient temperature on the gain of the preamplifier (dashed curve).

In Figure 11(b), the capacitance of the PVF_2 bimorph is plotted versus ambient temperature (dashed curve). Upon taking into account the gain characteristic shown in Figure 11(a), and accounting for the effect of capsule capacitance on insertion loss, the open circuit sensitivity of the capsule is derived, as in Figure 11(b) (solid curve). There is no significant change in the shape of the response curve over the temperature range -51°C to +71°C.

Upon return to room temperature following short term exposure, the performance of the PVF_2 microphone returns to normal.

4.3 HIGH AND LOW TEMPERATURE STORAGE

Figure 12 shows the amount of permanent loss of sensitivity, measured at room temperature, following exposure of a test microphone to extreme hot and cold temperatures. The exposure to hot temperatures consisted of 4 hours

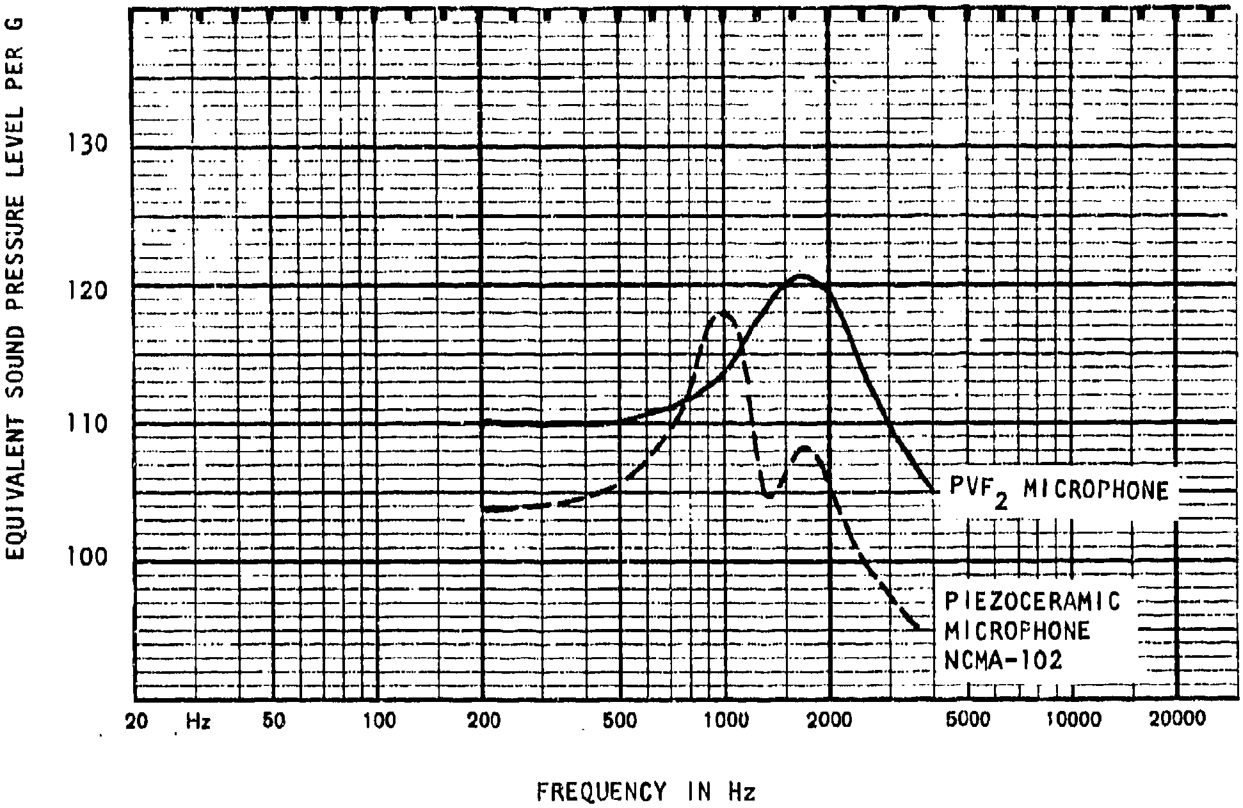
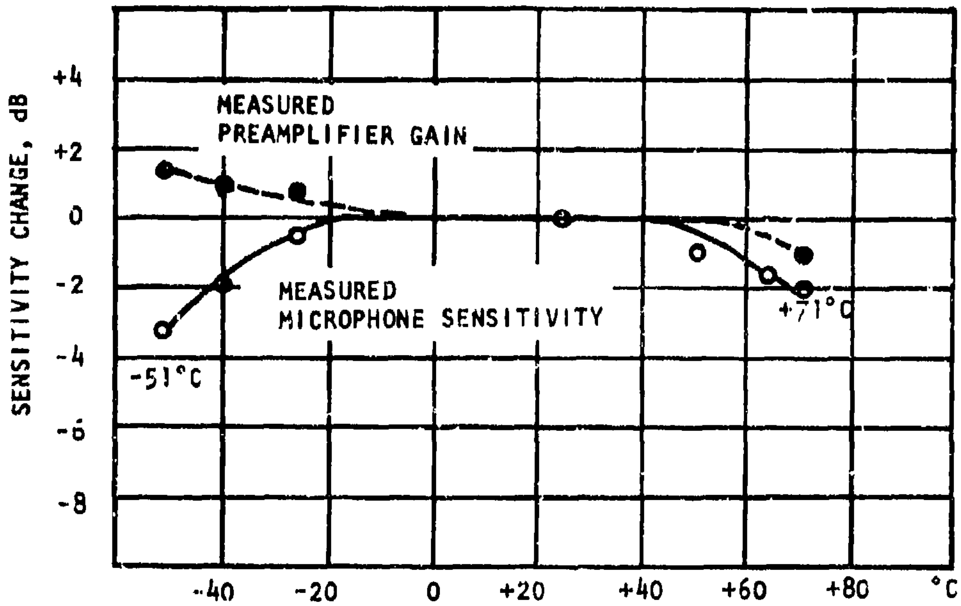
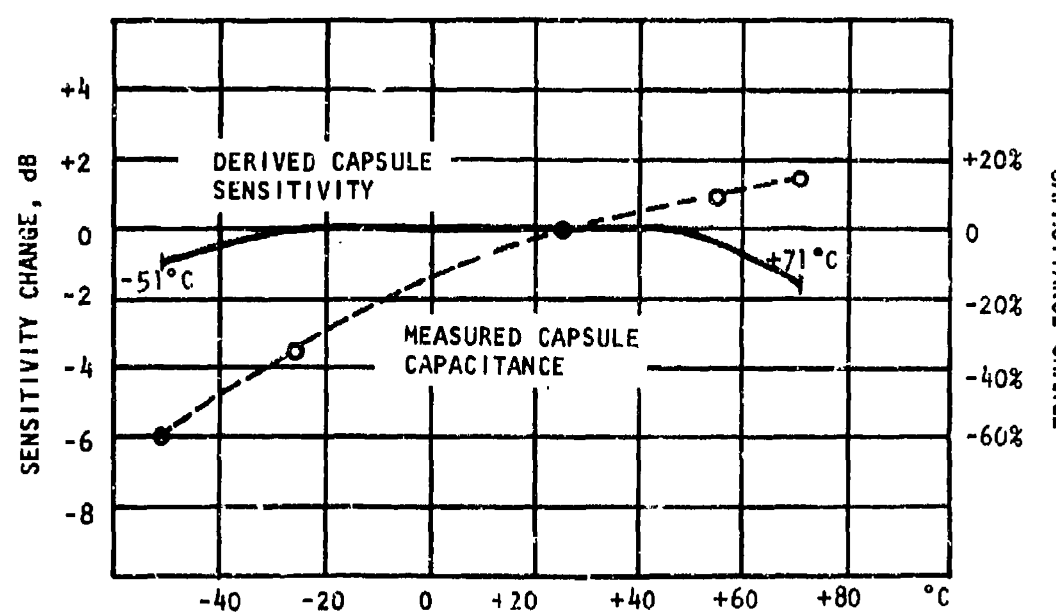


FIGURE 10. ACCELERATION RESPONSE



(a) MICROPHONE PERFORMANCE



(b) CAPSULE PERFORMANCE

FIGURE 11. EFFECT OF AMBIENT TEMPERATURE ON PVF_2 MICROPHONE

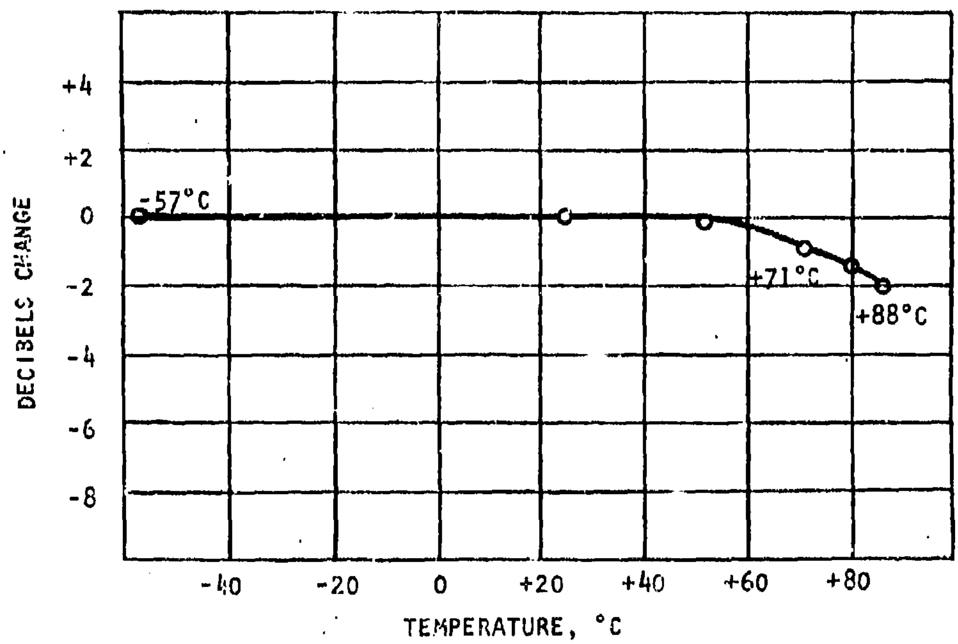


FIGURE 12. EFFECT OF STORAGE TEMPERATURE ON SENSITIVITY AT ROOM TEMPERATURE

at the indicated temperature, followed by overnight recovery at room temperature. This cycle was repeated twice, for a total of 3 cycles. A response and sensitivity measurement was then made. The three cycles were then repeated on the same microphone at the next higher indicated temperature. The permanent loss of sensitivity is attributed to depolarization of the PVF_2 film.

At the cold temperature, the test microphone was exposed to 2 hours at -57°C. Upon return to room temperature, there was no change in response or sensitivity.

4.4 HUMIDITY TEST

A test microphone was subjected to a 10-day humidity test (MIL-STD-810C, Method 506.1, Procedure I). There are ten 24-hour cycles in this test, each cycle consisting of 2 hours at 95% R.H. while the temperature is increased to 65°C (149°F), 6 hours at 65°C at 95% R.H., and 18 hours at or above 85° R.H. while the temperature is reduced to 30°C. After ten cycles the microphone was operated and found to be about 20 dB low in sensitivity. The response was normal. The preamplifier performance had not changed. The bimorph capacitance was about 25 pF, compared to the original 120 pF.

An analysis showed that a section of aluminum electrode was missing from the bimorph tabs at the point where the tabs join the main body of the bimorph. A probable reason is corrosion due to chemical reaction of the 45 LV epoxy bonding agent with the aluminum at the elevated temperature. This reaction may have been enhanced by the direct action of humid air reaching the tab, and by mechanical damage to the electrode due to flexing during assembly and handling, and due to the effect of high temperatures on the unconstrained PVF_2 tab.

Problems with the aluminum electrode did show up during the development of the microphone. During repeated testing of the same bimorph, loss of contact across the electrode sometimes occurred. It was also noted that if cured epoxy were lifted off the surface of the PVF film, the electrode would stay with the epoxy rather than the PVF_2. The effect of 100% humidity on the electrode was noted in Section 3.

4.5 IMMERSION TEST

There was no water leakage into the microphone, or change in performance after a 4-hour immersion test (MIL-STD-810C, Method 512, Procedure I).

5.0 CONCLUSIONS AND RECOMMENDATIONS

For operation over the temperature range of approximately -51°C (-60°F) to +71°C (160°F), the PVF_2 microphone Model NCMA-103 meets the U. S. Army's requirements for performance. The sensitivity and impedance are at the required level and response is flat from 200 Hz to 6000 Hz. The sensitivity and impedance can be adjusted by selection of resistors in the preamplifier.

As constructed, the microphone is water-tight and would be expected to survive standard tests for rain, dust, salt-fog, blast, vibration and shock. The microphone has been shown to survive storage at temperatures ranging from -57°C (-71°F) to +71°C (160°F).

The PVF_2 electrodes failed during the humidity test. This problem can be solved by careful redesign and selection of materials used in the assembly, or by an improvement in the durability of the electrode, or both.

The self-noise of the PVF_2 microphone is 12 dB higher than that of the previously developed piezoceramic microphone. Given a close-talking speech level of 28 μbar (103 dB SPL), the signal-to-noise ratio is 51 dB. During a talk test in a quiet ambient, the microphone self-noise is apparent and probably greater than desired.

The bimorph design may be close to optimum within the constraints of reasonable cost and use of common materials. The design depends on the use of a low-density stable material (aluminum) to control the bimorph rigidity over a relatively wide-temperature range. Some data cited in Appendix B suggests that, if it were not for this feature, the sensitivity of the microphone would be down 7 dB at 0°C and down 12 dB at -51°C.

The PVF_2 microphone may be compared to the piezoceramic microphone. The PVF_2 and piezoelectric bimorphs are physically interchangeable in the capsule, except for allowances for thickness. The PVF_2 bimorph has the advantage of being potentially less expensive. However, the PVF_2 bimorph is less sensitive, so more gain is required, which may increase the cost of the preamplifier.

The piezoceramic microphone is superior in all types of severe environments, and is generally superior in performance, particularly with regard to high output (low noise).

Overall, the piezoceramic microphone is preferred over the PVF_2 microphone. The preferred piezoceramic microphone would have the following features:

1. The size and acoustic design of the capsule and case should be adopted from that of the PVF_2 microphone, which is generally more compact and rugged. The PVF_2 capsule design is easier to assemble.

2. A bimorph-support configuration should be used which substantially eliminates sensitivity to vibration.

3. An integrated circuit preamplifier should be developed which incorporates the high input impedance, low noise, filter characteristics and 2-wire operation required in piezoelectric microphones. The FET-input, monolithic amplifiers which have been developed in the last few years can be the basis of such a preamplifier. A smooth roll-off of the response at 300 Hz is desirable. The response peak at 10,000 Hz can be attenuated by active-filtering in the preamplifier.

4. The piezoceramic microphone must be shielded against electromagnetic interference.

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APPENDIX A

DESIGN CALCULATIONS FOR A PVF_2 BIMORPH

Figure A-1 shows the constituent layers of a simply-supported bimorph annulus, such as shown in Figure 5. The expected performance of this bimorph will be calculated in this Appendix, using Standard International Units, and the following symbols:

- a outside radius of bimorph
- b inside radius
- c thickness of aluminum shim
- d thickness over the first pair of epoxy layers
- e thickness over the PVF_2 layers
- f thickness over the second pair of epoxy layers
- t overall thickness
- ρ density per unit area of plate
- E Young's modulus
- ν Poisson's ratio of material, $\nu = 0.33$ assumed for all materials
- g_{31} piezoelectric constant for stress in the stretched direction
- g_{32} piezoelectric constant for stress transverse to the stretched direction
- D flexural rigidity of plate, newton-meters
- λ^2 a function of b/a, $\lambda^2 = 9$ for $b/a = .78$
- K dielectric constant of PVF_2, $K = 13$
- ε_o permittivity of free space, $\varepsilon_o = 8.85 \times 10^{-12}$ farads/meter

The thickness of each PVF_2 film is $\frac{1}{2}$ (e-d).

The resonance frequency of a simply-supported annulus is[1]

$$f_r = \frac{\lambda^2}{2\pi a^2} \sqrt{D/\rho} \tag{1}$$

The area density is found by summing the area densities of each of the layers. Equation (1) does not include the contribution of the mass of the dome. The stiffness of the dome is assumed negligible.

The flexural rigidity D is given by[2]

$$D = 2 \int_o^{t/2} \frac{Ez^2}{1-\nu^2}\, dz \tag{2}$$

E and ν are functions of z. The origin of z is at the neutral axis. Integrating (2) for the bimorph shown in Figure A-1,

NOTE: SHADED LAYERS ARE EPOXY

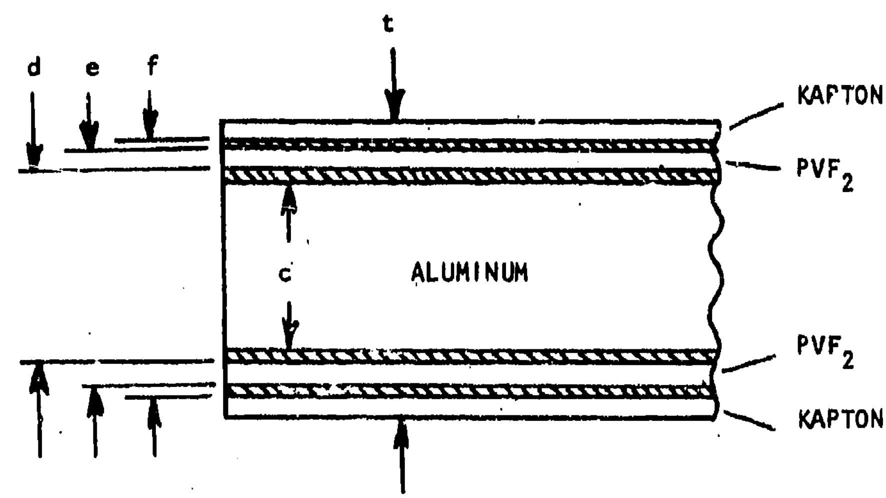

FIGURE A-1. BIMORPH LAYERS

$$D = \frac{1}{12}\{[\frac{Ec^3}{1-\nu^2}]_{Alum} + [\frac{E(d^3-c^3)}{1-\nu^2}]_{epoxy}$$

$$+ [\frac{E(e^3-d^3)}{1-\nu^2}]_{PVF_2} + [\frac{E(f^3-e^3)}{1-\nu^2}]_{epoxy} + [\frac{E(t^3-f^3)}{1-\nu^2}]_{Kapton}\} \qquad (3)$$

The capacitance C of the bimorph (series connection) is

$$C = K\varepsilon_o \frac{\pi(a^2-b^2)}{e-d} \qquad (4)$$

If sound pressure acts on a bimorph annulus, both tangential and radial bending moments are produced.[2] For either moment, the corresponding stress $\sigma(R)$ is a function of the distance r from the axis. At any point there is an angle θ between the direction of the stress and the stretched direction of the PVF_2. The local voltage output is then

$$v(\theta,r) = [g_{31}\sigma(r)\cos\theta + g_{32}\sigma(r)\sin\theta][e-d]$$

The voltage V(r) averaged over all (equally probable) values of θ is

$$V(r) = \frac{2}{\pi}\int_0^{\pi/2} v(\theta,r)\,d\theta = \frac{2}{\pi}(g_{31} + g_{32})\,\sigma(r)(e-d) \qquad (5)$$

Thus, for the bimorph annulus, an effective g constant can be defined for PVF_2.

$$g = \frac{2}{\pi}(g_{31} + g_{32}) = \frac{2}{\pi}(.174 + .017) = .122 \text{ volt-meters/newton}$$

The voltage sensitivity V/P of the simply-supported bimorph (series connection) with dome, for uniformly applied pressure P is[3]

$$V/P = \frac{1}{16}(g\frac{E}{1-\nu^2})_{PVF_2}(a^2+b^2)(e^2-d^2)\frac{1}{D} \qquad (6)$$

Equations (1), (4), and (6) can be used to predict the performance of the PVF_2 bimorph used in the Model NCMA-103. Table A-1 gives the material constants. The bimorph dimensions are as follows (in meters).

a	5.7×10^{-3} meters	(0.225 inches)
b	4.4×10^{-3}	(0.175 inches)
c	240×10^{-6}	(0.0095 inches)

TABLE A-1

Material	Aluminum	Epoxy	PVF_2	Kapton
Thickness (each layer)	240 μm	16	28	25
Volume density	2700 kg/m^3	1200	1780	1400
Young's modulus E	7.1×10^{10} N/m^2	2.4×10^9	3×10^9	3×10^9
Poisson's ratio ν	0.33	0.33	0.33	0.33
Effective g	-	-	0.122v-m/N	-
Dielectric constant K	-	-	13	-
Area density ρ (all layers)	0.65 kg/m^2	0.08	0.10	0.07
Flexural rigidity D (all layers)	0.092 N-m	0.004	0.005	0.006

d 272×10^{-6}
e 328×10^{-6}
f 360×10^{-6}
t 410×10^{-6} (0.016 inches)

The total contribution of each material to the flexural rigidity, calculated from Equation (3), is shown in the last row of Table A-1. The contribution to area density is also shown in Table A-1. As can be seen, about 86% of the rigidity is due to the aluminum shim.

Using Equation (1), the resonance frequency of the bimorph annulus is calculated to be $f_r = 15200$ Hz. This calculation does not include the mass of the dome or that of the bead of epoxy on the dome. When these masses are added to the estimated dynamic mass of the annulus, f_r falls to 12100 Hz.

The capacitance of the PVF_2 lead is significant, so that about 25% must be added to the capacitance obtained by Equation (4). The capacitance also absorbs some of the charge which is developed by the bimorph; the bimorph sensitivity calculated by Equation (6) is correspondingly less by about 2.0 dB.

Equation (6) applies to a pressure microphone. The effective close-source sensitivity of a noise-cancelling microphone is somewhat less due to the effect of sound pressure which reaches the rear side of the diaphragm.

The following table shows the calculated and typical measured open-circuit performance.

	Calculated	Measured
f_r	12,100 Hz	10,000 Hz
C	100 pF	120 pF
V/P (pressure)	-90 dBV/μbar	Approx. -93 dBV/μbar
V/P (noise-cancelling)	-	-97 dBV/μbar

The sensitivity of Equation (6) to parameter variations is instructive. If the thicknesses of all constituent layers of the bimorph are maintained in proportion, then $e^2 - d^2 \sim t^2$. Further assuming that the ratio b/a is constant,

$$V/P \sim a^2 t^2 \frac{1}{D} \sim a^2/t \tag{7}$$

Changing the thickness causes f_r to vary. Substituting from Equation (1) and (3) where $D/\rho \sim t^2$, $f_r \sim t/a^2$; then

$$V/P \sim 1/f_r \tag{8}$$

Equation (8) shows that, as expected, bandwidth can be traded for sensitivity. There are some ways of improving the bandwidth-sensitivity product which would be interesting subjects for future work, such as using exotic materials (e.g., beryllium), or putting a stiffness-controlling metal film on the PVF_2 in place of the Kapton water-barrier.

The use of a thicker film of PVF_2 would produce a proportionate increase in sensitivity, but with an accompanying increase in electrical impedance. Films of about 1-mil thickness appear to be the thickest which are readily available.

A point design of a bimorph which has a 5-mil aluminum shim instead of a 9.5-mil shim predicts the following performance as a pressure microphone. The aluminum still provides over 60% of the rigidity.

f_r	5500 Hz
C	100 pF
V/P	-76 dBV/μbar

Acoustic damping would be required, as in conventional noise-cancelling microphones.

More conventional PVF_2 bimorph assemblies, such as cantilevered beams, are potentially applicable to the PVF_2 microphone, although at the cost of a separate diaphragm, acoustic damping, and a more complicated assembly.

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APPENDIX B

DESIGN CALCULATIONS FOR A PVF_2 DOME

Figure B-1 shows a dome-shaped generating element[1] similar to that used in a commercial headset, the Pioneer Model SE-500. The surfaces of the dome are metallized to form two electrodes. In the SE-500 the concave side of the dome is pressed against a piece of plastic foam.

It can be shown that, for a ratio R/t of at least about 300, and a R/r of at least about 2, the stresses due to the built-in support can be neglected compared to the membrane stress.[2] The membrane stress σ is

$$\sigma = \frac{PR}{2t} \tag{1}$$

P sound pressure

R spherical radius

t thickness of shell

In the case of membrane stress, the stresses in the shell are equal in all directions tangent to the shell surface. If the PVF_2 is uniaxially stretched during manufacture, the voltage output is

$$V = g_{31}\sigma t + g_{32}\sigma t = (g_{31} + g_{32})\ \sigma t \tag{2}$$

g_{31} piezoelectric constant in the stretched direction, 0.174 V-m/N

g_{32} piezoelectric constant transverse to the stretched direction, 0.017 V-m/N

The microphone sensitivity, S = V/P, is

$$S = (g_{31} + g_{32})\ R/2 \tag{3}$$

The capacitance C is

$$C = K(8.85 \times 10^{-12})\ \frac{2\pi R(R-\sqrt{R^2-r^2})}{t} \tag{4}$$

K dielectric constant, 13

Again assuming only membrane stresses, i.e., that the surface moves like a portion of a pulsating sphere, the resonance frequency can be shown to be:

$$f_r = \frac{1}{2\pi}\sqrt{2E/\rho R^2} \tag{5}$$

E Young's modulus, 3.0×10^9 N/m^2

ρ Volume density, 1780 kg/m^2

Possible resonances due to transverse wave motion in the dome have not been considered in this calculation.

The resonance frequency and sensitivity are independent of radius r and independent of the film thickness. A design example is as follows.

R	25 mm
r	7.5 mm (Diam. = 0.58 inches)
t	.030 mm
f_r	11700 Hz
C	640 pF
S	-72 dBV/μbar

This example agrees very well with an actual microphone, described in Reference 1, which had a sensitivity of -74 dBV/μbar, capacitance of 700 pF, and resonance frequency (with plastic foam) of 7500 Hz. The plastic foam probably adds mass to the system.

Some experimental dome-diaphragms were assembled and tested. The typical capacitance was 1000 pF. All of the domes which were tested had a radius of curvature of 15 mm.

The domes were made of 1-mil thick PVF_2. They were formed against a metal mold at about 110°C (230°F) by pressing with a silicone-rubber pad. Figure B-1 shows the predicted and measured response of a typical unit. Apparently the forming temperature did not damage the PVF_2.

In Figure B-1, the measured response shows irregularities in the frequency range 5000-10,000 Hz. This is probably due to bending of the dome surface. If a soft plastic foam is pressed against the concave surface of the dome, the response is smoothed in this region, with no change in sensitivity. This may not be practical for an operational microphone which must withstand severe environments.

Environmental tests were made on other dome transducers. A summary of results follows.

Operate at Temperature (Unit #8)

Temperature	Sensitivity	Capacitance	200 - 6000 Hz Response
23°C	-81 dBV/μbar	660 pF	Normal
0°C	7 dB loss	10% loss	Normal
-51 °C	12 dB loss	60% loss	Normal
23°C - 38°C	No change	No change	Normal
+71°C	7 dB gain	15% gain	See discussion

The sensitivity variation with temperature is probably due to changes in Young's modulus of the PVF_2. Following low temperature exposure, the performance returned to normal. During exposure above +38°C (100°F), the dome began to dimple and flatten. This happens within a few minutes at +71°C (160°F), causing the response to become very irregular. Upon return to room temperature, the capacitance returned to normal, the response remained irregular, and the sensitivity was a couple of dB high due to flattening of the dome (increase in R).

Storage at temperature (Unit #7)

No permanent change due to storage at -57°C. The dome was damaged at +71°C as noted above.

Humidity (Unit #7)

No evident damage to the PVF_2 due to humidity. However, humidity at 65°C caused the aluminum coating to come off. Kreha film was used for the dome.

Forming of the dome must be done at a relatively low temperature so as not to affect the piezoelectric activity. Unfortunately, the resultant unrelieved stress in the dome causes it to become deformed during high temperature storage.

Calculations showed that a 0.25 μm coating of chromium or nickel on each side of the film would suitably constrain the PVF_2 and also provide a protecting barrier. A thickness of 0.25 μm of chromium was vapor-deposited on one side of a PVF_2 dome. The heat associated with the deposition process caused the dome to be deformed.

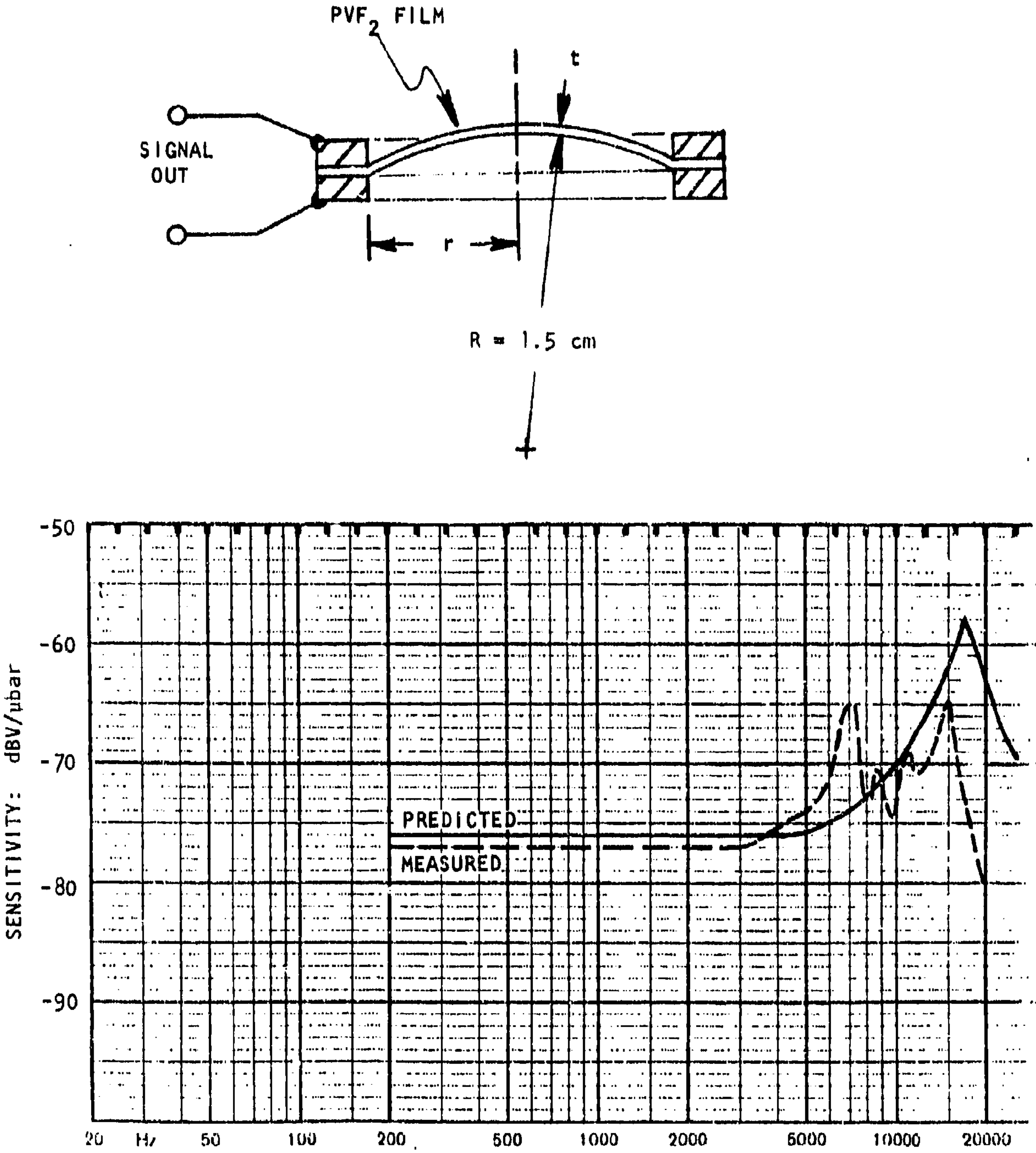

FIGURE B-1. RESPONSE OF EXPERIMENTAL PVF_2 DOME TRANSDUCER
(NO MOISTURE BARRIER)

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APPENDIX C

EFFECT OF SOUND-SOURCE ON APPARENT MICROPHONE SENSITIVITY

Figure C-1 shows the effect of the sound-source configuration on the sensitivity of the PVF_2 microphone, Model NCMA-103. The Air Force source is essentially a 1/4-inch diameter hole, in the wall of a long, 1 5/8-inch diameter tube. A speaker is coupled to one end of the tube. The other end has a sound-absorbing termination. The Air Force source was specified by the U. S. Army for the measurements described in this report.

The B&K 4216 Artificial Mouth has an internal 1/2-inch diameter capacitor microphone, located with its grille in the plane of the monuth opening. The microphone is used in a feedback loop to maintain the sound pressure constant at that location.

For each measurement of the PVF_2 microphone, the sensitivity was compared at the same distance to that of a 1/4-inch diameter capacitor microphone (B&K Type 4135).

The following table shows comparative data for sensitivity and noise-immunity at 1000 Hz.

Source	Distance	Sensitivity	Derived Noise-Immunity
Drawing 58B12627	1/4-inch	-90 dBV/μbar	12.0 dB
B&K 4216	1/4-inch	-93.5	8.5
B&K 4216	1/2-inch	-94.0	8.0

The change in the shape of the peak at 10,000 Hz was not investigated, but may be due to standing waves between the source and the PVF_2 microphone, or its mounting hardware. Due to its smaller area, the Air Force source is more like a point source than the B&K 4216. Therefore, the Air Force source will produce a higher pressure gradient at a given distance.

The sensitivity of noise-cancelling microphones depends in part on the distance between sound entries. Therefore, the magnitude of the effect reported here may not be applicable to other noise-cancelling microphones.

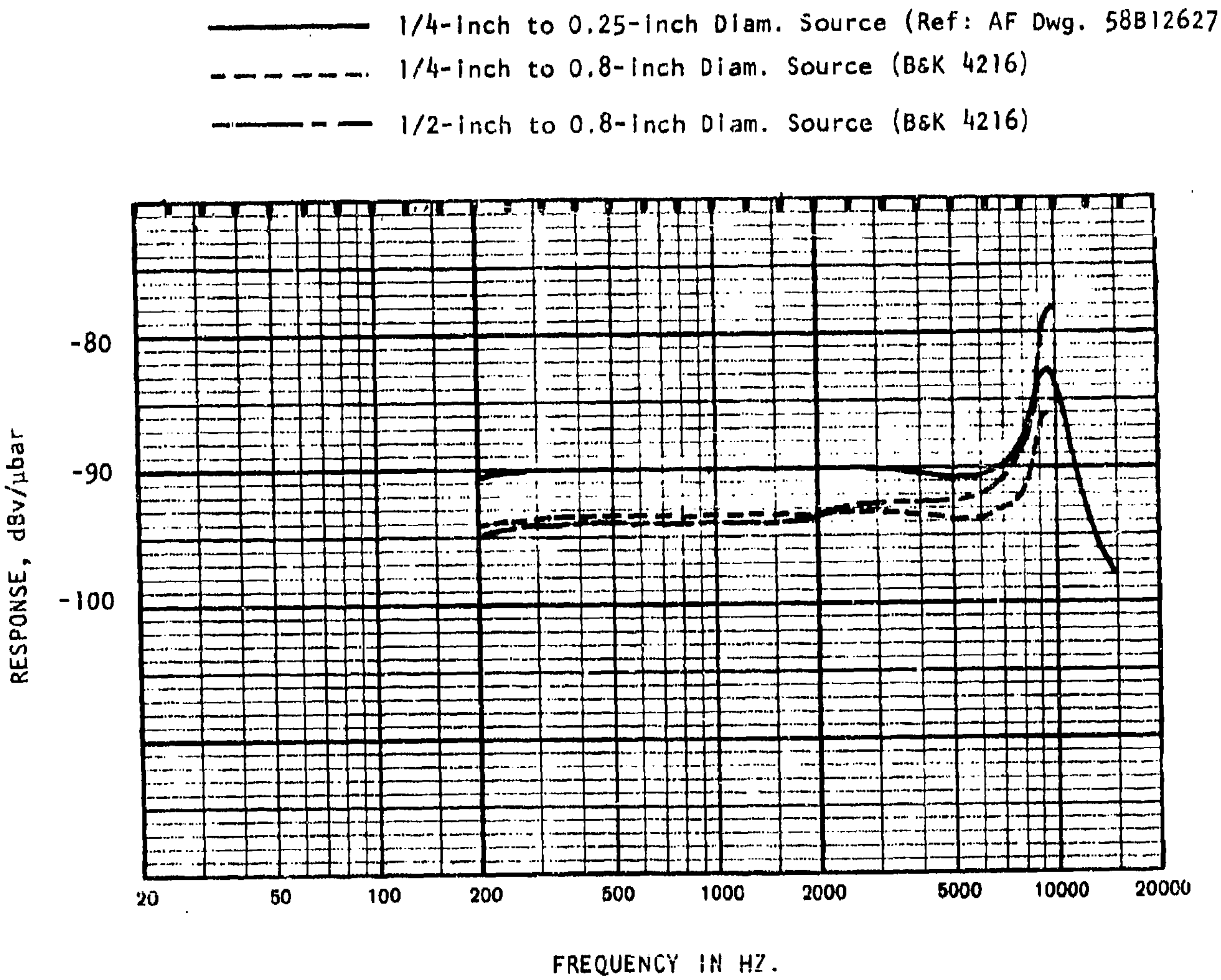

FIGURE C-1: EFFECT OF CLOSE-TALK SOUND SOURCE ON SENSITIVITY AND RESPONSE.

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